


 Cite this: *RSC Adv.*, 2022, **12**, 29826

# Molybdenum disulfide (MoS<sub>2</sub>) based photoredox catalysis in chemical transformations

 Praveen P. Singh,<sup>a</sup> Surabhi Sinha,<sup>a</sup> Geetika Pandey<sup>b</sup> and Vishal Srivastava<sup>b,\*c</sup>

Photoredox catalysis has been explored for chemical reactions by irradiation of photoactive catalysts with visible light, under mild and environmentally benign conditions. Furthermore, this methodology permits the activation of abundant chemicals into valuable products through novel mechanisms that are otherwise inaccessible. In this context, MoS<sub>2</sub> has drawn attention due to its excellent solar spectral response and its notable electrical, optical, mechanical and magnetic properties. MoS<sub>2</sub> has a number of characteristic properties like tunable band gap, enhanced absorption of visible light, a layered structure, efficient photon electron conversion, good photostability, non-toxic nature and quantum confinement effects that make it an ideal photocatalyst and co-catalyst for chemical transformations. Recently, MoS<sub>2</sub> has gained synthetic utility in chemical transformations. In this review, we will discuss MoS<sub>2</sub> properties, structure, synthesis techniques, and photochemistry along with modifications of MoS<sub>2</sub> to enhance its photocatalytic activity with a focus on its applications and future challenges.

 Received 9th September 2022  
 Accepted 11th October 2022

DOI: 10.1039/d2ra05695j

[rsc.li/rsc-advances](https://rsc.li/rsc-advances)

## 1 Introduction

Molybdenum disulfide (MoS<sub>2</sub>) is an inorganic compound of the transition metal dichalcogenide (TMD) series. It is one of the most used photocatalysts that has a wide range of applications in different fields. It is applicable to degrade pharmaceutically active compounds (PhACs), synthetic dyes (rhodamine B,

methylene blue, methyl orange and novacron red Hunts-man), pesticides and herbicides. It also employed for photocatalytic evolution of oxygen, nitrogen fixation, ammonia synthesis and water electrolysis.<sup>1-7</sup>

In recent years, MoS<sub>2</sub> has received much attention due to its unique electrical and optical properties.<sup>8a</sup> MoS<sub>2</sub> is a two-dimensional (2D) transition metal dichalcogenide, a narrow band semiconductor with a band gap of 1.9 eV which can be altered by adjusting the number of layers. Among all 2D TMDs, MoS<sub>2</sub> is one of the few with a natural layered structure, indicating that MoS<sub>2</sub> can be stripped to obtain high-quality 2D MoS<sub>2</sub> without complicated chemical synthesis.<sup>8b</sup> Therefore, the cost of preparing 2D MoS<sub>2</sub> is much lower than other 2D TMDs due to

<sup>a</sup>Department of Chemistry, United College of Engineering & Research, Prayagraj 211002, Uttar Pradesh, India. E-mail: ppsingh23@gmail.com

<sup>b</sup>Department of Physics, United University, Prayagraj 211012, Uttar Pradesh, India

<sup>c</sup>Department of Chemistry, CMP Degree College, University of Allahabad, Prayagraj-211002, Uttar Pradesh, India. E-mail: vishalgreenchem@gmail.com



*Praveen P. Singh is working as Assistant Professor in the Department of Chemistry at the United College of Engineering and Research, Prayagraj, India. He obtained his BSc, MSc degree in Organic Chemistry from T. D. P. G. College (V. B. S Purvanchal University) Jaunpur and DPhil from the Department of Chemistry, University of Allahabad, India. His current research interests include the develop-*

*ment of synthetic receptors for the recognition of biological target structures and the application of visible light chemical photocatalysis towards organic synthesis as well as nanophotocatalysis.*



*Surabhi Sinha is presently working as an Assistant Professor in the Department of Chemistry, United College of Engineering & Research, Naini, Prayagraj. She has completed her graduation, post-graduation and DPhil from the University of Allahabad, Prayagraj. Her area of research interest mainly includes quaternary complexes of biochemical significance and organic synthetic trans-*

*formations. She is a life member of several professional bodies.*



the simple synthesis conditions. More importantly, 2D MoS<sub>2</sub> is a 2D semiconductor with a direct band-gap, which has the best electric performance among 2D TMDs.<sup>8c</sup> These make 2D MoS<sub>2</sub> get more attention among 2D TMDs.

Several characteristics of MoS<sub>2</sub> such as high absorbance in the visible region,<sup>9</sup> high carrier mobility,<sup>10</sup> stability,<sup>11</sup> preferable catalytic activity,<sup>12</sup> good photostability,<sup>13</sup> outstanding electrochemical properties,<sup>14</sup> strong surface adsorption capacity and higher specific surface area<sup>15</sup> favours its application as a photocatalyst as well as a co-catalyst and also, it is capable of addressing the limitations faced by typical photocatalysts. Additionally, MoS<sub>2</sub> is found to be abundant and cheap.<sup>7</sup> Currently, semiconductor photocatalysts with controllable morphologies are gaining significant attraction in applications associated with environmental remediation process.<sup>16</sup> Phase engineering, defect engineering, doping of external materials, interlayer engineering, surface modification, and heterojunction<sup>17a,b</sup> construction make MoS<sub>2</sub> more flexible in terms of tuning its properties during synthesis.

Molybdenum disulfide (MoS<sub>2</sub>)<sup>17c</sup> has emerged as one of the most important two-dimensional functional materials, popular new co-catalysts due to their excellent photocatalytic activity, substantial adsorptivity, great value and its non-toxicity. The visible region of electromagnetic spectrum exhibits the absorption spectrum of 2D MoS<sub>2</sub>, providing a plethora of opportunities for widespread applications.<sup>17d</sup> Applications for MoS<sub>2</sub>-based materials are said to include energy storage,<sup>17e</sup> hydrogen production,<sup>17f</sup> pollutant degradation,<sup>17g</sup> disinfection,<sup>17h</sup> etc. Numerous studies have recently provided a summary of photocatalytic properties of MoS<sub>2</sub> for numerous application areas.<sup>17i-n</sup>

In continuation of our work on photocatalysed organic synthesis<sup>18,19</sup> this review aims to provide a comprehensive report on the current research, especially the role of MoS<sub>2</sub> in the chemical transformation.

## 2 Synthesis of MoS<sub>2</sub>

For the most part, two different synthetic procedures are used to create MoS<sub>2</sub>: (1) a top-down strategy that involves exfoliating

bulk MoS<sub>2</sub> to create materials with one or two monolayers, and (2) a bottom-up strategy that uses techniques like hydrothermal or chemical vapour deposition. Several methods exist for the preparation of MoS<sub>2</sub> using different molybdenum precursors and sulfur sources, like elemental sulfur powder,<sup>20</sup> thiourea,<sup>21</sup> thioacetamide,<sup>22</sup> and L-cysteine.<sup>23</sup> By regulating variables such the reaction solvent, temperature, pH, reaction time, and the application of surfactants or ligands, which are essential for managing the synthesis to create the desired chalcogenide, a variety of fascinating morphologies can be created. Table 1 exhibits the different methods that have been used to synthesize MoS<sub>2</sub> materials alongside the applications of the synthesized materials. The most used methods are solid-state,<sup>24</sup> hydrothermal,<sup>25,26</sup> solvothermal,<sup>27</sup> and hybrid methods.<sup>28,29</sup>

The benefits and drawbacks of synthesis techniques<sup>44</sup> such as thermal annealing, plasma-assisted synthesis, magnetron sputtering-based synthesis, atomic layer deposition (ALD), and wet chemical processes are summarised in Fig. 1.

## 3 Properties of MoS<sub>2</sub>

MoS<sub>2</sub> is a typical and stable 2D transition metal dichalcogenide which reveals that it is a semiconductor of MX<sub>2</sub> type where the transition metals denote M and the chalcogen denotes X<sup>45</sup> with three hexagonal planes (S–Mo–S), which is bonded to each other *via* ionic-covalent interactions.<sup>46</sup> The sandwiched MoS<sub>2</sub> is brought together to form sheets with an interlayer distance of 0.65 nm by the weak van der Waals force, which assumes responsibility for creating a 2D layered structure. Fig. 2a depicts the MoS<sub>2</sub> structure as described. In addition, Fig. 2b reflects the fact that the presence of impurities in MoS<sub>2</sub> alters its interlayer distance.<sup>47</sup> As an n-type semiconductor, MoS<sub>2</sub> has an indirect band gap of 1.2 eV in the bulk. The band gap of this semiconductor is inversely proportional to its number of layers. As a result, a direct band gap of 1.9 eV is obtained by almost reducing the number of layers to just one (Fig. 3c), making it a suitable photocatalyst in the visible region.<sup>41</sup> The narrow band gap facilitates its high absorption of light in the visible region.



*Geetika Pandey is working as an Assistant Professor in the Department of Physics at the United University, Prayagraj, India. She obtained her BSc, MSc degree in Physics and DPhil from the Department of Physics, University of Allahabad, Prayagraj, India. Her current research interests include the condensed matter physics and photocatalysis of nanomaterials.*



*Vishal Srivastava is working as an Assistant Professor, Department of Chemistry, C.M.P. College, (Constituent P.G. College of Central University of Allahabad) Prayagraj, India. He has completed his graduation (BSc), post-graduation (MSc) in Organic Chemistry and Doctoral Degree (DPhil) from the Department of Chemistry, University of Allahabad, India. His current research work involves the designing of novel biologically active photoredox catalysed synthetic organic compounds.*



Table 1 Synthesis Methods and Applications of MoS<sub>2</sub>

No.	Synthesis method	Metal precursor used	Source of sulfur used	Morphology and particle size	Applications	Ref.
1	Colloidal	Mo(CO) <sub>6</sub>	Sulfur powder	Nanosheets	Electrochemical studies	1
2	Hydrothermal	(NH <sub>4</sub> )Mo <sub>7</sub> O <sub>24</sub> ·4H <sub>2</sub> O	Thiourea (H <sub>2</sub> CSNH <sub>2</sub> )	Layered MoS <sub>2</sub> nanoflowers with ~0.1 μm particle size	Photocatalytic degradation of methylene blue and crystal violet dyes	2
3	Hydrothermal	Sodium molybdate dihydrate (Na <sub>2</sub> MoO <sub>4</sub> ·2H <sub>2</sub> O)	Thioacetamide (C <sub>2</sub> H <sub>5</sub> NS)	Nano flowers with average size ~100 nm	Photocatalytic degradation of rhodamine B	3
4	Hydrothermal	Sodium molybdate dihydrate (Na <sub>2</sub> MoO <sub>4</sub> ·2H <sub>2</sub> O)	L-cysteine	Quantum dots with ~2.5 nm particle size	Detection of methyl parathion (pesticide)	4
5	Hydrothermal	(NH <sub>4</sub> )MoS <sub>4</sub>	(NH <sub>4</sub> )MoS <sub>4</sub>		Fluorescent probe for hyaluronidase detection	5
6	Chemical Exfoliation	Commercially available MoS <sub>2</sub> powder		Nanosheets	Photocatalytic oxidation of benzyl halides	6 30
7	Chemical vapor Deposition	Ammonium heptamolybdate	Sulfur	Not mentioned		7 31
8	Colloidal	Ammonium tetrathiomolybdate [(NH <sub>4</sub> ) <sub>2</sub> MoS <sub>4</sub> ]	Ammonium tetrathiomolybdate [(NH <sub>4</sub> ) <sub>2</sub> MoS <sub>4</sub> ]	Spherical quantum dots with average size ~5 nm	Bioimaging	8 32
9	Heating	Mo(acac) <sub>2</sub>	1-Dodecanethiol	Nanosheet	Electrical bistability performance	9 33
10	Hot injection	Molybdenum(v) chloride (MoCl <sub>5</sub> )	N,N'-diphenylthiourea	Nanosheets		10 34
11	Hydrothermal	Sodium molybdate dihydrate (Na <sub>2</sub> MoO <sub>4</sub> ·2H <sub>2</sub> O)	Thioacetamide (CH <sub>3</sub> CSNH <sub>2</sub> )	Coral-like	Lubrication additive; photocatalytic degradation of liquid paraffin	11 35
12	Hydrothermal	Na <sub>2</sub> MoO <sub>4</sub> ·2H <sub>2</sub> O	Cysteine	Quantum dots with 2 ~3.5 nm particle size	Fluorescent probe for sensing of hydroquinone and bioimaging	12 36
13	Solid state	(NH <sub>4</sub> ) <sub>6</sub> Mo <sub>7</sub> O <sub>24</sub> ·4H <sub>2</sub> O	Sulfur	Nanosheets, thinner than 5 nm	Photocatalytic degradation of rhodamine B	24
14	Hydrothermal	Na <sub>2</sub> MoO <sub>4</sub> ·2H <sub>2</sub> O	Thiourea (H <sub>2</sub> CSNH <sub>2</sub> )	Irregular with average size in the range 12–25 nm	Electrochemical studies	25
15	Hydrothermal	Ammonium hepta molybdate tetrahydrate [(NH <sub>4</sub> ) <sub>6</sub> Mo <sub>7</sub> O <sub>24</sub> ·4H <sub>2</sub> O]	Ammonium polysulfide	Ammonium polysulfide as the sulfur source: Uniform MoS <sub>2</sub> nanospheres with average size of ~100 nm	Lubrication additive	27
16	Hydrothermal	MoO <sub>3</sub>	Potassium thiocyanate	Flowerlike MoS <sub>2</sub> spheres with average diameter of 1–2 nm	Photocatalytic degradation of methylene blue	37
17	Hydrothermal	Na <sub>2</sub> MoO <sub>4</sub> ·2H <sub>2</sub> O	L-cysteine	Microspheres comprising crossed-linked nanorods ~100 nm in length	Photocatalytic degradation of thiocarbamate herbicides	38
18	Hydrothermal	Ammonium tetrathiomolybdate [(NH <sub>4</sub> ) <sub>2</sub> MoS <sub>4</sub> ]	Thiourea (H <sub>2</sub> CSNH <sub>2</sub> )	Flowerlike microsphere	Photocatalytic degradation of rhodamine B and methylene blue	39
19	Hydrothermal	(NH <sub>4</sub> ) <sub>6</sub> Mo <sub>7</sub> O <sub>24</sub> ·4H <sub>2</sub> O	Thiourea	Nanosheets	Detection of dopamine	40
20	Hydrothermal	(NH <sub>4</sub> ) <sub>6</sub> Mo <sub>7</sub> O <sub>24</sub> ·4H <sub>2</sub> O	Na <sub>2</sub> S	Hierarchical porous with the thickness of ~20–40 nm	Detection of phenol sulphite oxidase, nicotinamide adenine dinucleotide oxidase and superoxide dismutase mimicking activities	41
21	Microwave	Ammonium tetrathiomolybdate [(NH <sub>4</sub> ) <sub>2</sub> MoS <sub>4</sub> ]	Ammonium tetrathiomolybdate [(NH <sub>4</sub> ) <sub>2</sub> MoS <sub>4</sub> ]	Quantum dots with average diameter of ~1.72 nm	Determination of terramycin	42
22	Solid state	(NH <sub>4</sub> ) <sub>2</sub> MoS <sub>4</sub>	Thiourea	Sheetlike structure and ultrathin layers	Electrochemical measurement	43

Crystal lattices of MoS<sub>2</sub> exists in four polymorphic forms namely 1H, 2H, 1T and 3R (H- Hexagonal, T-Tetragonal and R-Rhombohedral) which are classified based on the stacking arrangement and the co- ordination between Mo and S atoms

(Fig. 2d).<sup>11</sup> MoS<sub>2</sub> is synthesized in various morphologies (Fig. 2e) which includes nanoflowers (Fig. 2e<sub>1</sub>, Fig. 2e<sub>2</sub>),<sup>48</sup> nanosheets (Fig. 2e<sub>3</sub>, Fig. 2e<sub>4</sub>),<sup>49</sup> nanoflakes,<sup>50</sup> nanocrystals, nanospheres,<sup>51</sup> nanoribbons,<sup>52</sup> nanotubes (Fig. 2e<sub>5</sub>),<sup>53</sup> nanoworms (Fig. 2e<sub>6</sub>),<sup>54</sup>



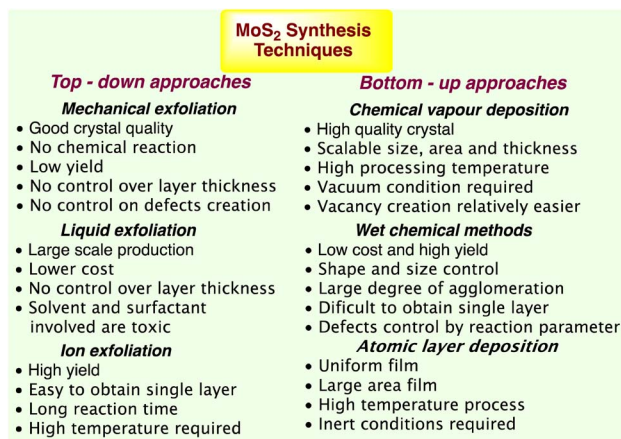


Fig. 1 MoS<sub>2</sub> synthesis techniques with their advantages and disadvantages.<sup>44</sup>

coral-like structures (Fig. 2e<sub>7</sub>),<sup>49</sup> nanodots and quantum dots (Fig. 2e<sub>8</sub>).<sup>55</sup>

Due to the 2D nature of MoS<sub>2</sub>, its intrinsic properties are greatly influenced by the surrounding environment on the nanoscale. The suspended structures in these systems are

hybrid systems with transport performance,<sup>56a-g</sup> tunable optoelectronic behaviour,<sup>56h-l</sup> and nanomechanical properties,<sup>56m-p</sup> all of which are fascinating on their own. The size, surface area, and surface energy of the MoS<sub>2</sub> particles are determined by its morphology, which has a significant impact on how it executes in photocatalytic applications. Due to their large surface area and narrow band gap, MoS<sub>2</sub> nanoflowers are more effective for absorption of visible light, which improves their photocatalytic efficacy. The shape of MoS<sub>2</sub> nanoflowers determines their surface area, which in turn determines how well they operate as photocatalysts. MoS<sub>2</sub> is anisotropic, piezocatalytic,<sup>56</sup> hydrophobic and low-toxic, which has high specific surface area with high surface energy,<sup>57</sup> high surface to volume ratio, high e<sup>-</sup> mobility, high optical absorption, high catalytic activity, good tribological properties,<sup>58</sup> good thermal stability and free sulfur groups.<sup>59</sup> Due to its low price and a wealth of earth reserves, it is commercially viable. As a result, MoS<sub>2</sub>'s characteristics are largely in favour of its application as a photocatalyst.

Unfortunately, the catalytic activity of MoS<sub>2</sub> is greatly inhibited due to its low dispersion ability which can be attributed to its hydrophobicity and low electrical conductivity.<sup>60</sup> The formation of composites using MoS<sub>2</sub> may be a viable and efficient way to get around this problem and maximise the benefits of MoS<sub>2</sub> as a photocatalyst in aqueous bodies because the

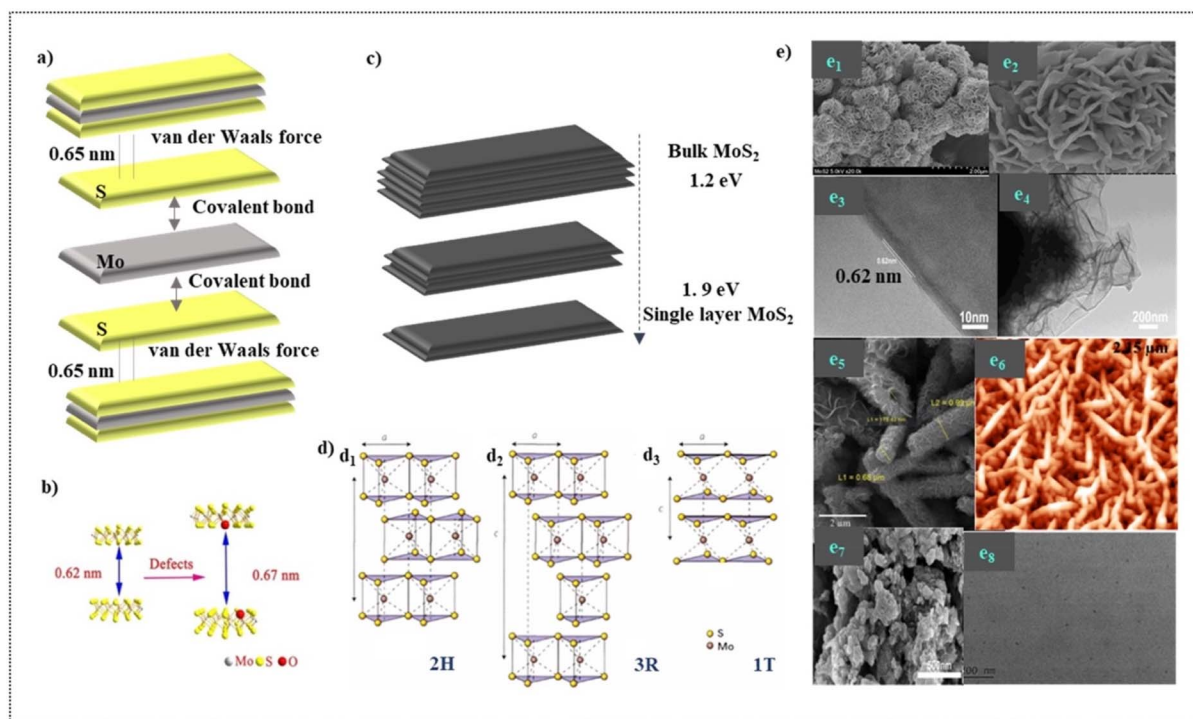


Fig. 2 (a). Visualization of the layered structure of MoS<sub>2</sub> and the forces responsible for its layered structure. (b). Pictorial illustration of the increased interlayer distance due to the presence of impurities. Adapted with permission from ref. 47, Copyrights 2022 Elsevier. (c). Graphical illustration of the tunable band gap exhibited by MoS<sub>2</sub>. (d). Crystal structures of MoS<sub>2</sub>. (d<sub>1</sub>). 2H, (d<sub>2</sub>). 3R and (d<sub>3</sub>). 1T. Adapted with permission from ref. 11, Copyrights 2022 Elsevier. (e). Different morphologies portrayed by MoS<sub>2</sub> (through synthesis) (e<sub>1</sub>). Nanoflowers at the resolution of 2 μm (e<sub>2</sub>). Nanoflowers at the resolution of 500 nm Adapted with permission from ref. 48, Copyrights 2022 Elsevier (e<sub>3</sub>). TEM image of the nanosheets at 10 nm (e<sub>4</sub>). TEM image of the nanosheets at 200 nm Adapted with permission from ref. 49, Copyrights 2022 Elsevier (e<sub>5</sub>). Nanotubes Adapted with permission from ref. 53, Copyrights 2022 Elsevier (e<sub>6</sub>). Nanoworms. Adapted with permission from ref. 54, Copyrights 2022 Elsevier (e<sub>7</sub>). Coral-like structure. Adapted with permission from ref. 49 Copyrights 2022 Elsevier (e<sub>8</sub>). Quantum dots. Reproduced from ref. 55 with permission from [Elsevier], Copyright [2022].





Fig. 3 Schematic illustration of the photocatalytic mechanism of MoS<sub>2</sub>. Reproduced from ref. 29 with permission from [American Chemical Society], copyright [2022].

properties of other compounds in the composite may enhance the electrical conductivity and dispersion of MoS<sub>2</sub> and thereby facilitate the exhibition of its full potential and surplus advantages.

## 4 Photochemistry of MoS<sub>2</sub>

MoS<sub>2</sub> has attracted significant attention, and a wide range of desirable photocatalytic properties have been reported, such as narrow band gap energy, excellent optical absorptivity, and high mobility of charge carriers, in addition to low toxicity and cost. However, the performance of MoS<sub>2</sub> is limited by photo-generated e<sup>-</sup>/h<sup>+</sup> recombination, the edge activity effect, and photocorrosion. Past efforts to enhance the photocatalytic properties of MoS<sub>2</sub> have involved controlling the morphology, modulation of energy bands through doping, band alignment through heterojunction formation, modification with carbon nanostructures, and combining with metal particles exhibiting surface plasmon resonance.

The photocatalytic redox processes begin with the production of photoexcited charge carrier pairs (e<sup>-</sup>/h<sup>+</sup>). As illustrated in Fig. 3, upon irradiation the MoS<sub>2</sub> simultaneously generates e<sup>-</sup> and h<sup>+</sup>,

where the photogenerated e<sup>-</sup> is promoted to the CB, leaving behind the hole (h<sup>+</sup>) in the VB. Subsequently, these photo-generated carriers migrate to the surface of the MoS<sub>2</sub> to participate in reduction (e<sup>-</sup>) and oxidation (h<sup>+</sup>) processes. Photoexcited e<sup>-</sup> may react with adsorbed O<sub>2</sub> to produce <sup>·</sup>O<sub>2</sub><sup>-</sup> radicals and, simultaneously, the h<sup>+</sup> remaining in the VB can abstract an e<sup>-</sup> from hydroxyl ions or adsorbed H<sub>2</sub>O molecules to produce <sup>·</sup>OH radicals, which are powerful oxidizing agents that can react with harmful organic, inorganic, and biological compounds.

## 5 Modifications of MoS<sub>2</sub> to improve its photocatalytic activity

The high e<sup>-</sup>/h<sup>+</sup> pair recombination efficiency of MoS<sub>2</sub> prevents it from being widely used in photocatalysis, despite the fact that it is a visible-light sensitive photocatalyst. This is a frequent problem with narrow band gap photocatalysts. Hence, to improve charge carrier separation, MoS<sub>2</sub> has been doped and coupled with many varied materials such as metals,<sup>61</sup> metal oxides,<sup>62</sup> and carbon-based materials.<sup>63</sup> Fig. 4 exhibits some of the modifications of MoS<sub>2</sub>. The doping of MoS<sub>2</sub> with metal or non-metal dopants, as shown in Fig. 4a and b, can generate defects and change the optical band gap of MoS<sub>2</sub>. Charge separation can be enhanced when associated with metals due to the existence of the metal–MoS<sub>2</sub> interface, as depicted in Fig. 4c. For instance, Cheah *et al.* reported an improved H<sub>2</sub> evolution activity of Ag@MoS<sub>2</sub> under irradiation by visible light.<sup>64</sup> They reported that the deposition of Ag onto MoS<sub>2</sub> assisted e<sup>-</sup> and h<sup>+</sup> separation, prevented charge recombination, and hence, enhanced the overall photocatalytic performance. By creating a band offset and/or an electric field across the space-charge area at the junction between the two materials, a heterojunction enables the separation of e<sup>-</sup>/h<sup>+</sup> pairs instantly. Fig. 4d shows the formation of two types of heterojunctions. A type I heterojunction results when the VB of MoS<sub>2</sub> is greater than the VB of the second semiconductor and the conduction band (CB) of MoS<sub>2</sub> is lower than the CB of the second semiconductor,

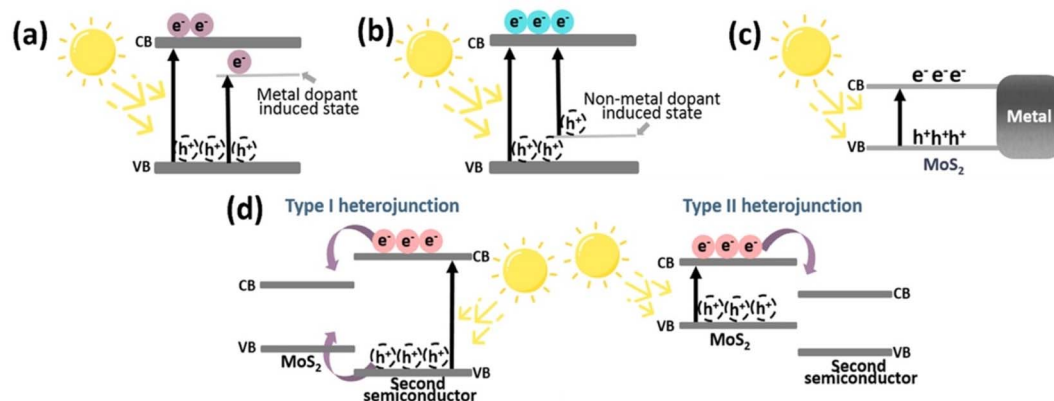


Fig. 4 Modifications of MoS<sub>2</sub> to improve its photocatalytic activity; (a) metal doping of MoS<sub>2</sub>, (b) nonmetal doping of MoS<sub>2</sub>, (c) metal deposited on MoS<sub>2</sub>, and (d) formation of a heterojunction with a second semiconductor. Reproduced from ref. 29 with permission from [American Chemical Society], copyright [2022].



## Review

allowing both electrons and holes to pass from the second semiconductor to the  $\text{MoS}_2$ . In contrast, a type II heterojunction is created when the VB of  $\text{MoS}_2$  is above the VB of the second semiconductor, acting as a hole sink, while the CB of the second semiconductor is below the VB of  $\text{MoS}_2$ , acting as an electron sink.<sup>65</sup> For example, Hu *et al.* reported that an optimized Co-doped  $\text{MoS}_2/\text{g-C}_3\text{N}_4$  heterojunction exhibited the highest activity for the photocatalytic reduction of water, with a  $\text{H}_2$  evolution rate of  $0.31 \text{ mmol g}^{-1} \text{ h}^{-1}$ .<sup>66</sup> According to these authors, Co-doped  $\text{MoS}_2$  has an edge-enriched 1T phase with more active sites than pristine  $\text{MoS}_2$ , as well as a heterojunction with  $\text{g-C}_3\text{N}_4$  to expedite charge transfer and separation and these factors contribute to the enhanced photocatalytic activity. Additionally, the creation of ternary and quaternary chalcogenides by including one or more additional elements into binary chalcogenides is a potential method for increasing the effectiveness of charge separation and interfacial charge transfer through the addition of additional surfaces. For example, Lim *et al.* fabricated a  $\text{ZnMoS}_4/\text{ZnO}/\text{CuS}$  p-n heterojunction photo-catalyst that results in a hydrogen evolution rate 97% higher than an unoptimized  $\text{ZnMoS}_4/\text{CuS}$  p-n structure.<sup>67</sup>

A hydrothermal and calcination technique is used to successfully create a Z-scheme  $\text{MoS}_2/\text{CuO}$  photocatalyst that degrades 2-mercaptobenzothiazole (MBT) with excellent activity (96 percent) when exposed to visible light<sup>68</sup> (Fig. 5a–e).

$\text{MoS}_2$  nanosheets and flower-shaped  $\text{CuO}$  combine to form a Z-scheme heterostructure, which significantly boosts the separation effectiveness of photogenerated carriers.  $\text{CuO}$  and  $\text{MoS}_2$ 's oxidation and reduction characteristics are enhanced by the Z-scheme electron transfer process that gives significant accumulation of photogenerated electrons and holes.

The authors proposed a possible Z-scheme charge transfer process and the reaction mechanism of MBT degradation by  $\text{MoS}_2/\text{CuO}$  heterojunction under visible light irradiation and the results are shown in Fig. 5f. Electron–hole pairs are generated by the excitation of both  $\text{MoS}_2$  and  $\text{CuO}$ . The electrons on the CB of  $\text{CuO}$  migrate to the VB of  $\text{MoS}_2$  and combine with holes on the VB of  $\text{MoS}_2$ . The photogenerated holes assembled by  $\text{CuO}$  can degrade MBT molecules in large quantities. In addition, due to the CB position of  $\text{MoS}_2$  is much more negative than the potential of  $\text{O}_2/\text{O}_2^-$ , the electrons on the CB of  $\text{MoS}_2$  will further undergo a reduction reaction to generate abundant  $\text{O}_2^-$ , which will be further involved in the degradation process. Although  $\text{CuO}$  has a higher negative VB potential than  $\text{OH}^-$ , it is theoretically impossible to form  $\text{OH}^-$ ; yet, some  $\text{OH}^-$  has been found using the ESR technique, which may be the result of further reducing  $\text{O}_2^-$ . The Z-scheme charge transfer mechanism for  $\text{MoS}_2/\text{CuO}$  significantly increases the separation efficiency of photogenerated carriers and positively influences the oxidizability and reducibility of the photocatalysts. Finally, the detailed photocatalytic reaction process of the Z-scheme  $\text{MoS}_2/\text{CuO}$  heterojunction is in Fig. 5f.

A S-scheme  $\text{MoS}_2/\text{g-C}_3\text{N}_4$  photocatalyst is developed<sup>69</sup> a one-pot solid-state reaction of thiourea and sodium molybdate as precursors at different temperatures under  $\text{N}_2$  gas was



Fig. 5 (a) SEM images of  $\text{CuO}$ , (b)  $\text{MoS}_2$ , (c)  $\text{MoS}_2/\text{CuO}$ , (d) TEM image of  $\text{MoS}_2/\text{CuO}$ , (e) elemental mapping of  $\text{MoS}_2/\text{CuO}$ . (f) photocatalytic degradation mechanism of MBT over the Z-scheme  $\text{MoS}_2/\text{CuO}$  heterojunction under visible light irradiation. Reproduced from ref. 68 with permission from [Royal Society of Chemistry], copyright [2020].

applied. The variation in component contents ( $\text{MoS}_2$  and  $\text{gC}_3\text{N}_4$ ) is determined by the physicochemical characterization of the final products *via* an increase in synthesis temperature. The morphology and elemental composition of representatives were investigated using field emission scanning electron microscopy (FE-SEM), high resolution transmission electron microscopy (HR-TEM), along with energy dispersive X-ray spectroscopy (EDS) mapping (Fig. 6a–g).

The degradation of Rhodamine B in an aqueous solution under visible light was used to evaluate the enhanced photocatalytic activity of the  $\text{MoS}_2/\text{gC}_3\text{N}_4$  composites. The best photocatalytic performance there was demonstrated by composites created at  $500^\circ\text{C}$ , with a degradation efficiency of 90%, which was significantly better than that of a single  $\text{g-C}_3\text{N}_4$ . The improvement in light harvesting and the extension in the lifetime of photoinduced charge carriers of composites, which are the result of the synergistic interaction between the components, are credited with the significant improvement in photocatalytic performance. Besides, the photocatalytic mechanism is demonstrated to well-fit into the S-scheme pathway with apparent evidences (Fig. 6h).





**Fig. 6** (a and b) FE-SEM; and (c and d) HR-TEM images of MCN-500; FE-SEM images of (e) MCN-600; and (f) CN-500; EDS mapping images of (g) mapping area, (g<sub>1</sub>) carbon, (g<sub>2</sub>) nitrogen, (g<sub>3</sub>) sulfur, and (g<sub>4</sub>) molybdenum, (h) schematic diagram of band alignment of heterojunction and S-scheme charge transfer on interface of MoS<sub>2</sub> and g-C<sub>3</sub>N<sub>4</sub>. Reproduced from ref. 69 with permission from [Springer Nature], copyright [2021].

## 6 Applications of MoS<sub>2</sub> based nano-photocatalyst for chemical transformations

The MoS<sub>2</sub> photocatalysis visible-light irradiation is considered a green alternative to traditional synthetic methodologies. As only mild conditions are needed and the formation of undesirable byproducts is decreased, it is a viable path for organic transformation processes. Summary of previous studies on photocatalytic organic transformation reactions using MoS<sub>2</sub>-based materials are tabulated in Table 2.

### 6.1 Cross-dehydrogenative coupling reaction

De *et al.* developed<sup>77a</sup> a methodology targeted for the utilization of sacrificial amine donors for C–H functionalization with MoS<sub>2</sub> quantum dots (QDs) as the catalyst as well as the photosensitizer. In fact, QDs has emerged to be an active participant in the heterogeneous electron transfer process. This approach brings up new opportunities for photomediated organic transformations using nanomaterials without the need for external photosensitizers using a non-toxic, long-lasting procedure. The reduction cycle produces H<sub>2</sub> from water, and the oxidative cycle culminates in the CDC product. (Fig. 7).

The authors proposed a mechanistic pathway for the CDC reaction parallel to the photochemical HER mediated by MoS<sub>2</sub> QDs (Fig. 7). An electron is excited from the valence band (VB) to the conduction band (CB) by radiation. In presence of O<sub>2</sub>, 2-Aryl-1,2,3,4-tetrahydroisoquinoline **1** is oxidized to radical cation **1**<sup>•+</sup> *via* transferring an electron to the VB to regenerate the ground state of the QD. There is no need of any external photosensitizer for the oxidation of **1**. The radical cation of **1** results the formation of iminium intermediate **1**<sup>+</sup> by losing a H<sup>•</sup>. The nucleophile **2** attacks the iminium intermediate **1**<sup>+</sup> to give the targeted cross-coupled product **3** with simultaneous evolution of H<sub>2</sub>. Thus, QDs act as a photosensitizer as well as a catalyst that also transfer electron for the water-splitting process and further regenerated in the process. In the proposed mechanism, they have stated that the source of H can be from H<sub>2</sub>O as well as the nucleophile NuH. As their target was to design a methodology for the CDC reaction, they did not carry out any deuterated experiments to confirm the source of H<sub>2</sub>.

De *et al.* also demonstrated<sup>77b</sup> 1T (metallic)-2H (semiconducting) phase boundaries intrinsic to individual sheets of chemically exfoliated 2D-MoS<sub>2</sub> that can serve as heterojunctions for enhanced photocatalysis compare to only semiconducting phase. Due to the abundance of heterojunctions in these multiphase materials, chemically exfoliated 2D-MoS<sub>2</sub> provides improved stability as well as transfer of photogenerated charges to the reactants, giving better yield. Significantly, they proved that this simple synthesized material works well as a photocatalyst for the aerobic oxidative coupling of amines to imines when subjected to visible light. Given its broad applications, they believe mixed phase 2D-MoS<sub>2</sub> can be of interest to several industrial synthetic applications related to semiconductor-based photocatalysis. An additional benefit is that this heterogeneous photocatalyst can be regenerated up to five times without significant loss in the activity (Fig. 8).

Further De *et al.*<sup>77c</sup> have developed an efficient method for Cross Dehydrogenative Coupling (CDC) reaction by using mixed phase 2D-MoS<sub>2</sub> nanosheets and Eosin Y alongside the photochemical Hydrogen Evolution Reaction (HER). The reaction has been carried out at room temperature under visible light irradiation and results in good to excellent yields. It is an example of a CDC reaction using mixed phase 2D-MoS<sub>2</sub> nanosheets as a catalyst regenerator and Eosin Y as photosensitizer. Due to incomplete recovery of the catalyst, the material can be reused with slight loss in the yields. Additionally, the scope of this protocol can be used to create various C–C coupled products. This could be an illustration of how to completely utilise the oxidation and reduction cycles of several semiconductor-based photocatalysts. (Fig. 9).

### 6.2 Suzuki–Miyaura coupling reaction

Lim *et al.* demonstrated<sup>78</sup> the incorporation of MoS<sub>2</sub> nanosheets with Pd nanodots is a promising way for promoting the visible-light-induced Suzuki–Miyaura C–C coupling reaction. The MoS<sub>2</sub> nanosheets decorated with Pd nanodots showed excellent photocatalytic activity. The turnover frequency for the biphenyl product was >1600 h<sup>-1</sup> even under sunlight illumination at



Table 2 Summary of previous studies on photocatalytic chemical transformation reactions using MoS<sub>2</sub>-based materials

S. N.	Application	Photocatalyst used	Morphology	Particle size	Light source	Performance	Ref.
1	Photocatalytic oxidation of benzyl alcohol to benzaldehyde	Co-doped MoS <sub>2</sub> /g-C <sub>3</sub> N <sub>4</sub>	2D nanosheet morphology with curly stripes		80 W LED lamp	Benzaldehyde production rate of 0.48 mmol g <sup>-1</sup> h <sup>-1</sup>	66
2	Photocatalytic oxidative coupling of thiols	Pd@Cu/MoS <sub>2</sub>	Spherical	64.5 nm	300 W Xe lamp	~99% conversion under 400–800 nm irradiation	70
3	Photocatalytic reduction of 4-nitrophenol	TiO <sub>2</sub> hollow spheres/crumpled MoS <sub>2</sub> nanosheet	Hollow sphere	~200 nm	500 W Xe lamp	99.35% photocatalytic reduction of 4-nitrophenol	71
4	Photocatalytic conversion of CO <sub>2</sub> to methane	MoS <sub>2</sub> /Cu	MoS <sub>2</sub> nanosheets are coated on the surface of Cu nanorods	About 50–700 nm	300 W Xe lamp	Maximum yield of methane ~23 mmol g <sup>-1</sup> h <sup>-1</sup>	72
5	Photocatalytic reduction of CO <sub>2</sub> to methanol	MoS <sub>2</sub> grown on hexagonal boron nitride nanoplatelets	MoS <sub>2</sub> nanosheets are uniformly grown over the hexagonal boron nitride nanoplatelets	Each MoS <sub>2</sub> nanosheet is composed of 2–6 molecular lamellae	20 W white LED lamp	Maximum yield of methanol 5994 μmol g <sup>-1</sup>	73
6	Photocatalytic reduction of CO <sub>2</sub> to methane and CO	In <sub>2</sub> S <sub>3</sub> /MoO <sub>3</sub> @MoS <sub>2</sub>	Distorted hexagonal nanorods		300 W Xe lamp	Yield ~29.4 and ~35.6 μmol g <sup>-1</sup> h <sup>-1</sup> for CH <sub>4</sub> and CO, respectively	74
7	Photocatalytic selective oxidation of benzyl alcohols to benzaldehyde	Ag <sub>3</sub> PO <sub>4</sub> nanoparticle@MoS <sub>2</sub> quantum dot/few-layered MoS <sub>2</sub> nanosheet	Nanosheet		300 W Xe lamp	≤92% conversion of benzyl alcohol and ~87% yield of benzaldehyde after 3 h of irradiation	75
8	Photocatalytic reduction of 4-nitrophenol to 4-aminophenol	CdS-MoS <sub>2</sub> /rGO composite	Flowerlike morphology		500 W Xe lamp	≤70% reduction of 4-nitrophenol after 60 min of irradiation	76

room temperature. Mechanistic researches revealed that the high catalytic activity of MoS<sub>2</sub> originated from the efficient electron–hole pair generation mechanism under visible-light (Fig. 10).

### 6.3 Photocatalytic NH<sub>3</sub> synthesis

He *et al.* developed<sup>79</sup> the efficient photoreduction of N<sub>2</sub> to NH<sub>3</sub> over ternary MoS<sub>2</sub>/C–ZnO composite, that was prepared *via* a combination of hydrothermal and photodeposition method (Fig. 11).

Several methods were employed to characterise the produced composite, and the results displayed that carbon was loaded onto the surface of ZnO instead of doped into the lattice in order to prevent charge carrier recombination. By thermal processing, the carbon content of C–ZnO can be altered by which enhances the effectiveness of charge separation. For calcination, the most favourable temperature of 300 °C determined. The separation of electron–hole pairs can be further improved by photodepositing MoS<sub>2</sub> nanoparticles on the C–ZnO-300 sample, which traps electrons on the carbon layer. The ideal 1% MoS<sub>2</sub>/C–ZnO-300 composite exhibits the fastest NH<sub>3</sub> generation rate under simulated sunlight irradiation at 245.7 μmol L<sup>-1</sup> g<sup>-1</sup> h<sup>-1</sup>, which is 9.3 and 4.0 times higher than that of ZnO and C–ZnO, respectively. However, when exposed to visible light, C–ZnO performs best, producing NH<sub>3</sub> at a rate of 28.8 μmol L<sup>-1</sup> g<sup>-1</sup> h<sup>-1</sup>, indicating that the composite employs

a different process. The carbon layer was thought to act as a photosensitizer by transferring electrons to ZnO or MoS<sub>2</sub>. The processes proposed have been confirmed by EIS and PC evaluations. The addition of a carbon layer and MoS<sub>2</sub> nanoparticles to the ZnO increases the BET area. The increased surface area might be partially responsible for the higher photocatalytic performance. (Fig. 11a and b). There is another way to reduce N<sub>2</sub> to NH<sub>3</sub> *via* photocatalysis<sup>80,81</sup>.

### 6.4 Photoelectrochemical nitrogen reduction

The photoelectrochemical (PEC) technique, which uses both solar energy as well as electricity efficiently synthesise ammonia under ambient conditions. Han *et al.*<sup>82</sup> have been synthesized MoS<sub>2</sub>@LZO heterostructures by assembling 2D-MoS<sub>2</sub> nanoflakes on La<sub>2</sub>Zr<sub>2</sub>O<sub>7</sub> nanofibers *via* a facile hydrothermal method (Fig. 12a).

Due to the electrical dispersion in LZO, the homogeneous assembly of MoS<sub>2</sub>@LZO prevents the photogenerated electron hole pair from recombining more quickly. Superior PEC-NRR performances can be seen as a result of the interaction between the localised electronic distribution in the MoS<sub>2</sub>@LZO heterostructures, oxygen vacancies in La<sub>2</sub>Zr<sub>2</sub>O<sub>7</sub>, excellent conductivity of the nanofibers, and increased exposure of surface sites for electron–hole generation in MoS<sub>2</sub>. The trapped photoelectron during N<sub>2</sub> activation is donated by the reduction of N<sub>2</sub> to NH<sub>3</sub> at the oxygen vacancy, which serves as the



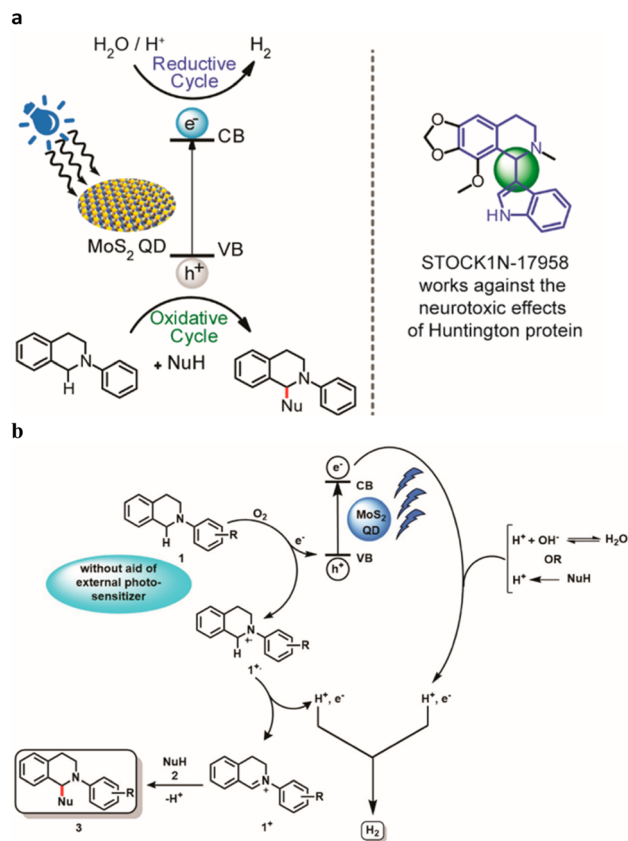


Fig. 7 (a) Photomediated oxidation and reduction cycle of MoS<sub>2</sub> QDs. (b) Proposed mechanism for the catalytic activity of MoS<sub>2</sub> blue QDs in CDC reaction synchronized with HER. Reproduced from ref. 77a with permission from [American Chemical Society], copyright [2022].

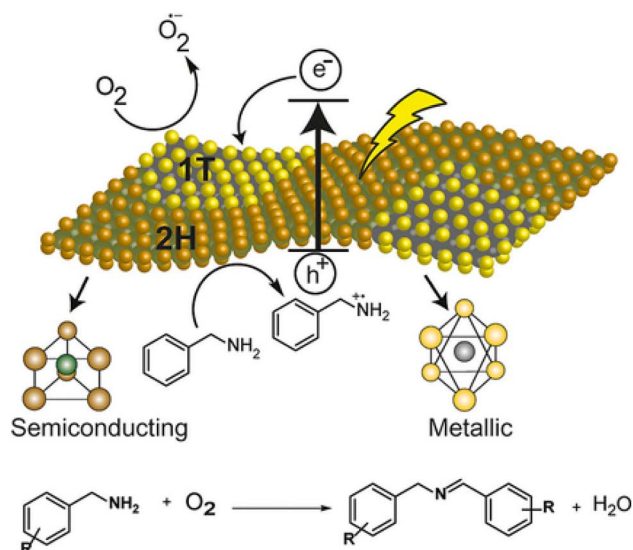


Fig. 8 Plausible mechanism for the oxidative coupling of benzylamine to imine photocatalyzed by mixed-phase 2D-MoS<sub>2</sub> nanosheets. Reproduced from ref. 77b with permission from [John Wiley & Sons, Inc.], copyright [2018].

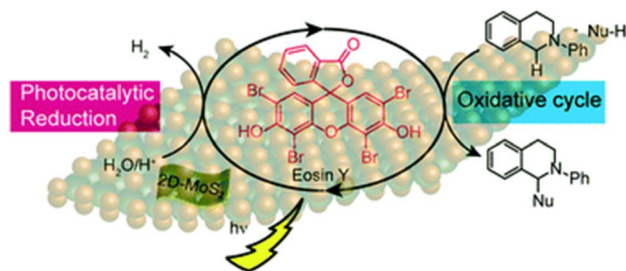


Fig. 9 Schematic illustration of the 2D-MoS<sub>2</sub> photocatalyzed oxidation and reduction cycles in presence of Eosin Y as photosensitizer. Reduction cycle produces H<sub>2</sub> from water as reported earlier, whereas oxidative cycle is responsible for CDC Reaction and formation of additional H<sub>2</sub>. Reproduced from ref. 77c with permission from [Royal Society of Chemistry], copyright [2019].

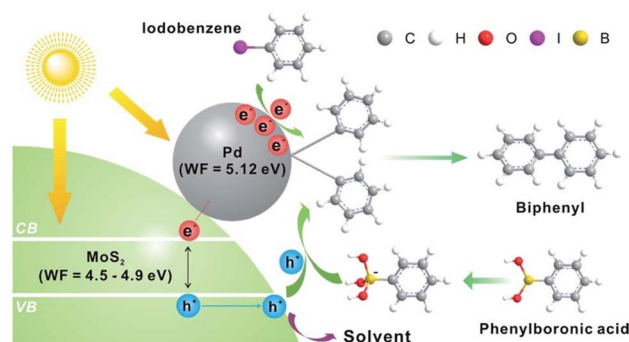


Fig. 10 The Pd-nanodot decorated MoS<sub>2</sub> micro/nanosheet for an efficient visible light induced photocatalytic Suzuki-Miyaura coupling reaction. Reproduced from ref. 78 with permission from [Royal Society of Chemistry], copyright [2017].

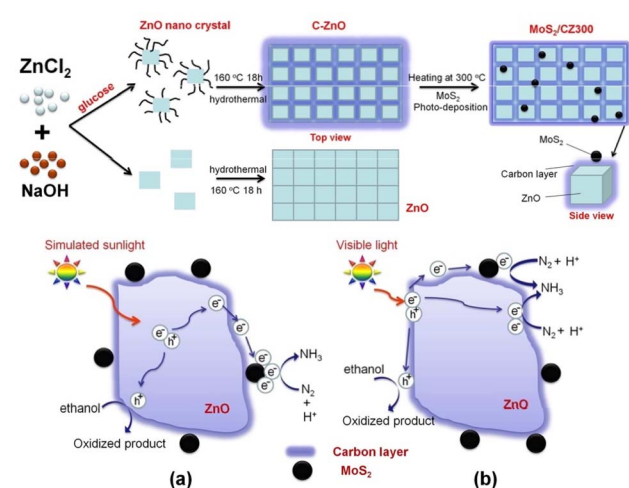


Fig. 11 Preparation of MoS<sub>2</sub>/CZ300 photocatalyst and the suggested charge transfer mechanism of MoS<sub>2</sub>/CZ300 composite (a) under simulated sunlight (b) and visible light irradiation. Reproduced from ref. 79 with permission from [American Chemical Society], copyright [2018].



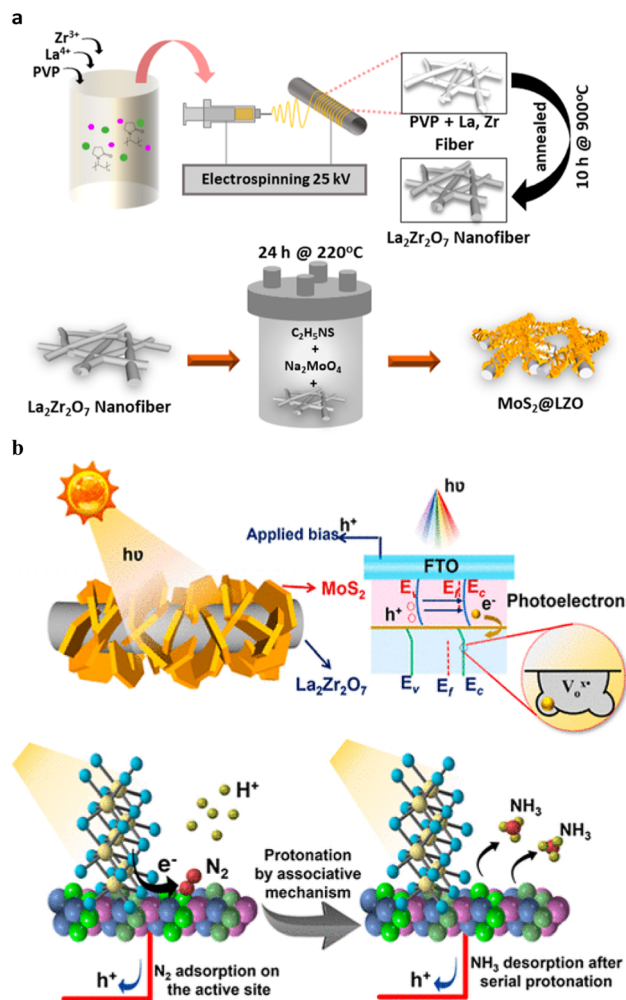


Fig. 12 (a) Schematic illustration of the electrospun LZO nanofibers, followed by hydrothermal synthesis of  $MoS_2@LZO$ . (b) The band structure demonstrating the type II heterojunction for  $MoS_2@LZO$  heterostructures with a reduced Fermi level under applied bias and solar illumination and schematic illustration of the PEC-NRR mechanism following the associative pathway for ammonia production. Reproduced from ref. 82 with permission from [American Chemical Society], copyright [2022].

active site for these reactions. The  $MoS_2@LZO$  PEC catalyst exhibits a maximum ammonia yield rate of approximately  $10.4 \mu\text{g h}^{-1} \text{cm}^{-2}$  and a higher faradaic efficiency of approximately 2.25% compared to pristine  $MoS_2$  and LZO. The heterostructure interface, which is rich in oxygen vacancies and offers a stable design with effective active sites, can be used to confirm this remarkable performance. Compared to the current  $MoS_2$  catalysts,  $MoS_2@LZO$  demonstrates a higher ammonia yield, selective  $N_2$  adsorption, and excellent stability. The 2D- $MoS_2$  nanoflakes, the  $La_2Zr_2O_7$  pyrochlore/fluorite structured nanofibers, and their heterostructure interfaces for enhanced ammonia production are presented with PEC-NRR mechanisms under ambient conditions. For various additional catalysis techniques to efficiently drive photoelectrocatalytic activity, the design strategy of inserting an n-type semiconductor over rich

oxygen-vacant stable nanostructures to establish an interface can be used. (Fig. 12b).

### 6.5 Photocatalytic oxidation of nitrite

Zheng *et al.* reported<sup>83</sup> the photocatalytic oxidation rate of  $NO_2^-$  under simulated solar irradiation, which can reach 62% by the  $MoS_2/TiO_2$  composite synthesized in a hydrothermal system with a  $C_2H_5NS/Na_2MoO_4$  molar ratio of 1 : 0.6 : under 200 °C for 24 h, which is significantly higher than that by pristine  $TiO_2$  NFs, P25 and pure  $MoS_2$ . The photocatalytic oxidation process of  $NO_2^-$  follows the Langmuir–Hinshelwood kinetic model (pseudo-first order reaction), and the reaction rate constant ( $k$ ) of the as-prepared composite is about  $0.19194 \text{ h}^{-1}$ .  $MoS_2$  considerably increases the ability of catalyst ability to absorb visible light, which promotes the production of electrons and holes and ensures the strong photoactivity of catalyst. The composite has an about 2.2 eV band gap, which indicates improved visible light absorption. The titanium substrate is permanently attached to the composite using this straightforward, low-consumption approach, enabling recycling and ecologically responsible implementation possible (Fig. 13).

### 6.6 Photocatalytic conversion of $CO_2$ and $H_2O$ to $CO$ , $CH_4$ and $H_2$ products

Ray *et al.* reported,<sup>84</sup> the integration of photoabsorber  $MoS_2$  and N-containing conducting polymer polypyrrole (PPy) over reduced graphene oxide improved  $CO_2$  photoreduction and  $H_2$  production (rGO). A variety of rGO- $MoS_2$ /PPy nanocomposites were created and morphologically, structurally, and optically studied using various methods. Under pretend sunlight the optimal rGO- $MoS_2$ /PPy nanocomposite was found to exhibit a remarkable production of  $CO$  ( $3.9 \mu\text{mol g}^{-1} \text{h}^{-1}$ ),  $CH_4$  ( $1.50 \mu\text{mol g}^{-1} \text{h}^{-1}$ ), and  $H_2$  ( $4.19 \mu\text{mol g}^{-1} \text{h}^{-1}$ ) in the photocatalytic reduction of  $CO_2$  in an aqueous suspension (Fig. 14).

The synergistic effect of the  $MoS_2$ , rGO, and PPy nanostructures, which encouraged the separation and migration of the photogenerated charges through the heterojunction interfaces and decreased electron–hole recombination, was

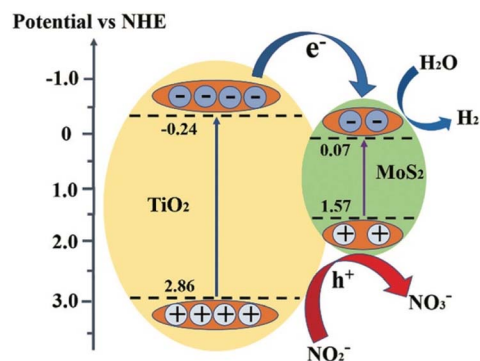


Fig. 13 Schematic illustration of the energy band structure and electron–hole separation of  $MoS_2/TiO_2$  composites. Reproduced from ref. 83 with permission from [Royal Society of Chemistry], copyright [2021].





Fig. 14 (a) Schematic representation of the band positions and potentials of PPy and MoS<sub>2</sub>. (b) Photocatalytic CO<sub>2</sub> conversion into CH<sub>4</sub> and CO gas via Z-scheme mechanism with rGO as redox mediator on the rGO-MoS<sub>2</sub>/PPy nanocomposite. (c) The conventional type II electron transfer for H<sub>2</sub> production on the rGO-MoS<sub>2</sub>/PPy nanocomposite. Reproduced from ref. 84 with permission from [American Chemical Society], copyright [2020].

attributed to the improvement in the photocatalytic performance of the highly active surface material rGO-MoS<sub>2</sub>/PPy-150. The PPy in the rGO-MoS<sub>2</sub>/PPy nanocomposite played multiple roles in improving the photocatalytic reduction of CO due to its superior conductivities, CO<sub>2</sub> adsorption capabilities *via* its amine groups, and electron storage qualities. Better catalytic performance is possible due to the reduced PPy concentration in nanocomposite. Importantly, the strong recycling performance of rGO-MoS<sub>2</sub>/PPy-150 nanocomposite revealed the robustness and stability of photocatalyst (Fig. 14a-c).

## 7 Future outlook

Although many studies have focused on the synthesis of MoS<sub>2</sub> and MoS<sub>2</sub>-based nanomaterials and their different uses, there are still a plethora of challenges:

1. MoS<sub>2</sub>-based materials will be extensively used in a variety of disciplines and could one day become commercially feasible because of their unique physical and chemical qualities. With this, MoS<sub>2</sub> will be applied to various media and released into the environment, potentially posing risks to both human health and the ecosystem. Therefore, a detailed evaluation of the toxicity of MoS<sub>2</sub>-based compounds is required.

2. The application of MoS<sub>2</sub>-based photocatalysts has so far been confined to laboratory-based research; it has not yet been investigated how well MoS<sub>2</sub> performs in real-world environments, and a perfect photocatalyst that can be used on a wide scale and in industry has not yet been developed.

3. Certain MoS<sub>2</sub> composites become unstable when exposed to visible light. Therefore, more investigation is required to design materials based on MoS<sub>2</sub> that are photosensitive.

4. A significant challenge pertains for the development of practical techniques for the generation of MoS<sub>2</sub> in quantities appropriate for industrial applications. For large-scale production, additional research into the scaling up of synthetic approaches is therefore needed.

## 8 Conclusion

In this review, we highlighted the different MoS<sub>2</sub> structures, their synthesising techniques and properties. The primary benefits and drawbacks of synthesis approaches were also summarised. MoS<sub>2</sub> is a promising material with a wide range of applications. MoS<sub>2</sub> and MoS<sub>2</sub>-based nanomaterials are currently the topic of extensive research as promising photocatalyst for the photocatalytic degradation and inorganic and organic chemical transformation. MoS<sub>2</sub> and MoS<sub>2</sub>-based materials have exceptional physicochemical features, due to which they exhibit wide range of synthetic applications like coupling reaction, oxidation, reduction as well as organic and inorganic compound production. This review relies on recent developments regarding the application of MoS<sub>2</sub> in chemical transformations. The prospects for successful visible-light-induced photocatalysis using MoS<sub>2</sub> based materials are finally discussed.

## Conflicts of interest

There are no conflicts to declare.

## References

- 1 A. Majumder, D. Saidulu, A. K. Gupta and P. S. Ghosal, *J. Environ. Manage.*, 2011, **293**, 112858.
- 2 A. L. Camargo-Perea, E. A. Serna-Galvis, J. Lee and R. A. Torres-Palma, *Ultrason. Sonochem.*, 2021, **73**, 105500.
- 3 Y. Rao, D. Xue, H. Pan, J. Feng and Y. Li, *Chem. Eng. J.*, 2016, **283**, 65–75.



- 4 M. H. F. Graumans, W. F. L. M. Hoeben, M. F. P. van Dael, R. B. M. Anzion, F. G. M. Russel and P. T. J. Scheepers, *Environ. Res.*, 2021, **195**, 110884.
- 5 P. Sharma, D. Kumar and S. Mutnuri, *J. Pharm. Anal.*, 2021, **11**, 320–329.
- 6 Q. Zhou, Y. Huang, Y. Zhang, C. Xu, W. Huang, K. Yang, X. Chen and Y. Zhang, *Mater. Chem. Phys.*, 2020, **276**, 125333.
- 7 Md. Ahmaruzzaman and V. Gadore, *J. Environ. Chem. Eng.*, 2021, **9**, 105836.
- 8 (a) X. Li, R. Shen, S. Mab, X. Chen and J. Xie, *Appl. Surf. Sci.*, 2018, **430**, 53–107; (b) E. Canadell, A. L. Beuze, M. A. E. Khalifa, R. Chevrel and M. H. Whangbo, *J. Am. Chem. Soc.*, 1989, **111**, 3778–3782; (c) J. N. Coleman, M. Lotya, A. O'Neil, S. D. Bergin, P. J. King, U. Khan, K. Young, A. Gaucher, S. De and R. J. Smith, *Science*, 2011, **331**, 568–571.
- 9 F. Guo, X. Huang, Z. Chen, H. Ren, M. Li and L. Chen, *J. Hazard. Mater.*, 2020, **390**, 12215.
- 10 R. N. Dalila, M. K. Md Arshad, S. C. B. Gopinath, W. M. W. Norhaimi and M. F. M. Fathil, *Biosens. Bioelectron.*, 2019, **132**, 248–264.
- 11 Y. Yuan, R. T. Guo, L. F. Hong, X. Y. Ji, Z. S. Li, Z. D. Lin and W. G. Pan, *Colloids Surf. A Physicochem. Eng. Asp.*, 2021, **611**, 125836.
- 12 S. Ni, L. Yang, H. Qu, X. Zhu, Z. Xu, M. Yuan, H. Xing, L. Wang, J. Yu and H. Liu, *J. Environ. Chem. Eng.*, 2021, **9**, 105101.
- 13 L. Cheng, W. Huang, Q. Gong, C. Liu, Z. Liu, Y. Li and H. Dai, *Angew. Chem., Int. Ed.*, 2014, **53**, 7860–7863.
- 14 S. Yin, Y. Ding, C. Luo, Q. Hu, Y. Chen, J. Di, B. Wang, J. Xia and H. Li, *Colloids Surf. A*, 2021, **609**, 125655.
- 15 L. Liu, J. Cao, M. Ali, J. Zhang and Z. Wang, *Environ. Adv.*, 2021, **4**, 100059.
- 16 M. Arumugam, Y. Yu, H. J. Jung, S. Yeon, H. Lee, J. Theerthagiri, S. J. Lee and M. Y. Choi, *Environ. Res.*, 2021, **197**, 111080.
- 17 (a) H. Wang, C. Li, P. Fang, Z. Zhang and J. Z. Zhang, *Chem. Soc. Rev.*, 2018, **47**, 6101–6127; (b) P. R. Sivaranjani, B. Janani, A. M. Thomas, L. L. Raju and S. S. Khan, *J. Cleaner Prod.*, 2022, **352**, 131506; (c) M. H. Wu, L. Li, N. Liu, D. J. Wang, Y. C. Xue and L. Tang, *Process Saf. Environ. Prot.*, 2018, **118**, 40–58; (d) K. F. Mak, C. Lee, J. Hone, J. Shan and T. F. Heinz, *Phys. Rev. Lett.*, 2010, **105**, 136805; (e) Y. Yuan, R.-t. Guo, L.-f. Hong, X.-y. Ji, Z.-s. Li, Z.-d. Lin and W.-g. Pan, *Colloids Surf., A*, 2021, **611**, 125836; (f) B. Han and Y. H. Hu, *Energy Sci. Eng.*, 2016, **4**, 285e304; (g) M.-h. Wu, L. Li, N. Liu, D.-j. Wang, Y.-c. Xue and L. Tang, *Process Saf. Environ. Prot.*, 2018, **118**, 40e58; (h) X. Meng, Z. Li, H. Zeng, J. Chen and Z. Zhang, *Appl. Catal. B: Environ.*, 2017, **210**, 160e172; (i) G. Zhang, H. Liu, J. Qu and J. Li, *Energy Environ. Sci.*, 2016, **9**, 1190e1209; (j) J. Theerthagiri, R. A. Senthil, B. Senthilkumar, A. Reddy Polu, J. Madhavan and M. Ashokkumar, *J. Solid State Chem.*, 2017, **252**, 43e71; (k) Z. Li, X. Meng and Z. Zhang, *J. Photochem. Photobiol. C*, 2018, **35**, 39e55; (l) Z. Liang, R. Shen, Y. H. Ng, P. Zhang, Q. Xiang and X. Li, *J. Mater. Sci. Technol.*, 2020, **56**, 89e121; (m) D. B. Sulas-Kern, E. M. Miller and J. L. Blackburn, *Energy Environ. Sci.*, 2020, **13**, 2684e2740; (n) N. Thomas, S. Mathew, K. M. Nair, K. O'Dowd, P. Forouzandeh, A. Goswami, G. McGranaghan and S. C. Pillai, *Mater. Today Sustain.*, 2021, **13**, 100073.
- 18 (a) V. Srivastava, P. K. Singh and P. P. Singh, *Croat. Chem. Acta*, 2015, **88**(1), 59–65; (b) V. Srivastava, P. K. Singh and P. P. Singh, *Croat. Chem. Acta*, 2015, **88**(3), 227–233; (c) V. Srivastava, P. K. Singh and P. P. Singh, *Asian J. Chem.*, 2016, **28**(10), 2159–2163; (d) V. Srivastava, P. K. Singh and P. P. Singh, *Croat. Chem. Acta*, 2017, **90**(3), 435–441; (e) V. Srivastava, P. K. Singh, S. Kanaujia and P. P. Singh, *New J. Chem.*, 2018, **42**, 688; (f) P. K. Singh, P. P. Singh and V. Srivastava, *Croat. Chem. Acta*, 2018, **91**(3), 383–387; (g) V. Srivastava, P. K. Singh and P. P. Singh, *Tetrahedron Lett.*, 2019, **60**, 40–43; (h) V. Srivastava, P. K. Singh and P. P. Singh, *Tetrahedron Lett.*, 2019, **60**, 1333–1336; (i) V. Srivastava, P. K. Singh and P. P. Singh, *Tetrahedron Lett.*, 2019, **60**, 151041; (j) V. Srivastava, P. K. Singh and P. P. Singh, *Rev. Roum. Chim.*, 2020, **65**(3), 221–226.
- 19 (a) V. Srivastava and P. P. Singh, *RSC Adv.*, 2017, **7**, 31377–31392; (b) V. Srivastava, P. K. Singh, A. Srivastava and P. P. Singh, *RSC Adv.*, 2020, **10**, 20046; (c) A. Srivastava, P. K. Singh, A. Ali, P. P. Singh and V. Srivastava, *RSC Adv.*, 2020, **10**, 39495; (d) V. Srivastava, P. K. Singh, A. Srivastava and P. P. Singh, *RSC Adv.*, 2021, **11**, 14251–14259; (e) V. Srivastava and P. P. Singh, *Org. Biomol. Chem.*, 2021, **19**, 313–321; (f) P. P. Singh, P. K. Singh, M. Z. Beg, A. Kashyap and V. Srivastava, *Synth. Commun.*, 2021, **51**(20), 3033–3058; (g) V. Srivastava, P. K. Singh, A. Srivastava, S. Sinha and P. P. Singh, *Photochem.*, 2021, **1**, 237–246; (h) V. Srivastava, P. K. Singh, S. Tivari and P. P. Singh, *Org. Chem. Front.*, 2022, **9**, 1485; (i) V. Srivastava, P. K. Singh and P. P. Singh, *J. Photochem. Photobiol., C*, 2022, **50**, 100488; (j) V. Srivastava and P. P. Singh, *RSC Adv.*, 2022, **12**, 18245.
- 20 M. Alam Khan and Y. M. Kang, Synthesis and Electrochemical Performance of Colloidal MoS<sub>2</sub> Nanosheets as an Anode Material in Sodium Ion Battery, *J. Energy Storage*, 2016, 252–257.
- 21 H. K. Sadhanala, S. Senapati, K. V. Harika, K. K. Nanda and A. Gedanken, *New J. Chem.*, 2018, **42**(17), 14318–14324.
- 22 J. S. Roy, G. Dugas, S. Morency and Y. Messaddeq, *Phys. Rev. E*, 2020, **120**, 114114.
- 23 N. Fahimi-Kashani, A. Rashti, M. R. Hormozi-Nezhad and V. Mahdavi, *Anal. Methods*, 2017, **9**(4), 716–723.
- 24 W. Chen, M. Liu, S. Wei, X. Li, L. Mao and W. Shangguan, *J. Alloys Compd.*, 2020, **836**, 155401.
- 25 C. Nagaraju, C. V. V. Muralee Gopi, J. W. Ahn and H. J. Kim, *New J. Chem.*, 2018, **42**(15), 12357–12360.
- 26 W. Gu, Y. Yan, C. Zhang, C. Ding and Y. Xian, *ACS Appl. Mater. Interfaces*, 2016, **8**(18), 11272–11279.
- 27 S. V. Prabhakar Vattikuti, C. Byon, C. Venkata Reddy, B. Venkatesh and J. Shim, *J. Mater. Sci.*, 2015, **50**(14), 5024–5038.
- 28 W. Chen, L. Sun, Q. Li, L. Huo and H. Zhao, *Int. J. Hydrogen Energy*, 2020, **45**(43), 22459–22468.



- 29 A. Rahman, J. R. Jennings, A. L. Tan and M. M. Khan, *ACS Omega*, 2022, **7**(26), 22089–22110.
- 30 N. Tian, Z. Li, D. Xu, Y. Li, W. Peng, G. Zhang, F. Zhang and X. Fan, *Ind. Eng. Chem. Res.*, 2016, **55**(32), 8726–8732.
- 31 J. H. Kim, J. Lee, S. Park, C. Seo, S. J. Yun, G. H. Han, J. Kim, Y. H. Lee and H. S. Lee, *Curr. Appl. Phys.*, 2022, **33**, 59–65.
- 32 H. Lin, C. Wang, J. Wu, Z. Xu, Y. Huang and C. Zhang, *New J. Chem.*, 2015, **39**(11), 8492–8497.
- 33 X. Li, A. Tang, J. Li, L. Guan, G. Dong and F. Teng, *Nanoscale Res. Lett.*, 2016, **11**(1), 171.
- 34 (a) Y. Liu, Q. Zhong, K. Chen, J. Zhou, X. Yang and W. Chen, *J. Mater. Sci.: Mater. Electron.*, 2017, **28**(18), 13633–13637; (b) L. Liu, Z. Huang, Y. Peng and P. Huang, *New J. Chem.*, 2017, **41**(15), 7674–7680.
- 35 L. Liu, Z. Huang, Y. Peng and P. Huang, *New J. Chem.*, 2017, **41**(15), 7674–7680.
- 36 L. Li, Z. Guo, S. Wang, D. Li, X. Hou, F. Wang, Y. Yang and X. Yang, *Anal. Methods*, 2019, **11**(26), 3307–3313.
- 37 B. Sheng, J. Liu, Z. Li, M. Wang, K. Zhu, J. Qiu and J. Wang, *Mater. Lett.*, 2015, **144**, 153–156.
- 38 S. Huang, C. Chen, H. Tsai, J. Shaya and C. Lu, *Sep. Purif. Technol.*, 2018, **197**, 147–155.
- 39 X. Zhang, H. Suo, R. Zhang, S. Niu, X. qi Zhao, J. Zheng and C. Guo, *Mater. Res. Bull.*, 2018, **100**, 249–253.
- 40 M. Sabar, U. Amara, S. Riaz, A. Hayat, M. Nasir and M. H. Nawaz, *Mater. Lett.*, 2022, **308**, 131233.
- 41 Y. Cai, L. Niu, X. Liu, Y. Zhang, Z. Zheng, L. Zeng and A. Liu, *J. Hazard. Mater.*, 2022, **425**, 128053.
- 42 X. Yu, Y. Meng, Y. Yan, X. Jin, G. Ni and J. Peng, *Microchem. J.*, 2020, **152**, 104406.
- 43 U. Chothe, C. Ugale, M. Kulkarni and B. Kale, *Crystals*, 2021, **11**(6), 660.
- 44 S. Singh, A. Modak, K. Ki. Pant, A. Sinhamahapatra and P. Biswas, *ACS Appl. Nano Mater.*, 2021, **4**(9), 8644–8667.
- 45 V. Singh and S. Rath, *Syst. Nanostruct.*, 2021, **128**, 114617.
- 46 V. Hasija, P. Raizada, V. K. Thakur, A. A. P. Khan, A. M. Asiri and P. Singh, *J. Environ. Chem. Eng.*, 2020, **8**, 104307.
- 47 M. Guo, Z. Xing, T. Zhao, Y. Qiu, B. Tao, Z. Li and W. Zhou, *Appl. Catal. B Environ.*, 2020, **272**, 118978.
- 48 K. Talukdar, K. Saravanakumar, Y. Kim, A. Fayyaz, G. Kim, Y. Yoon and C. M. Park, *Composites Part B*, 2021, **215**, 108780.
- 49 L. Luo, M. Shi, S. Zhao, W. Tan, X. Lin, H. Wang and F. Jiang, *J. Saudi Chem. Soc.*, 2021, **23**, 762–773.
- 50 X. Bai, H. Lv, Z. Liu, J. Chen, J. Wang, B. Sun, Y. Zhang, R. Wang and K. Shi, *J. Hazard. Mater.*, 2021, **416**, 125830.
- 51 J. Singh, S. R. Kumar and R. K. Soni, *J. Alloys Compd.*, 2020, **849**, 156502.
- 52 H. Jing, *Chem. Phys.*, 2021, **548**, 111241.
- 53 M. Nazifi, A. M. Ramezani, G. Absalan and R. Ahmadi, *Sens. Actuators, B*, 2021, **332**, 129459.
- 54 A. Neetika Kumar, R. Chandra and V. K. Malik, *Thin Solid Films*, 2021, **725**, 138625.
- 55 Y. Jiao, Q. Huang, J. Wang, Z. He and Z. Li, *Appl. Catal., B*, 2019, **247**, 124–132.
- 56 (a) A. Cepellotti, G. Fugallo, L. Paulatto, M. Lazzeri, F. Mauri and N. Marzari, *Nat. Commun.*, 2015, **6**, 6400; (b) G. Fugallo, A. Cepellotti, L. Paulatto, M. Lazzeri, N. Marzari and F. Mauri, *Nano Lett.*, 2014, **14**, 6109–6114; (c) X. Xu, L. F. C. Pereira, Y. Wang, J. Wu, K. Zhang, X. Zhao, S. Bae, C. T. Bui, R. Xie, J. T. L. Thong, B. H. Hong, K. P. Loh, D. Donadio, B. Li and B. Ozyilmaz, *Nat. Commun.*, 2014, **5**, 3689; (d) S. Ghosh, W. Bao, D. L. Nika, S. Subrina, E. P. Pokatilov, C. N. Lau and A. A. Balandin, *Nat. Mater.*, 2010, **9**, 555–558; (e) A. A. Balandin, S. Ghosh, W. Bao, I. Calizo, D. Teweldebrhan, F. Miao and C. N. Lau, *Nano Lett.*, 2008, **8**, 902–907; (f) A. A. Balandin, *MRS Bull.*, 2014, **39**, 817–823; (g) A. Branny, S. Kumar, R. Proux and B. D. Gerardot, *Nat. Commun.*, 2017, **8**, 15053; (h) C. Palacios-Berraquero, D. M. Kara, A. R. P. Montblanch, M. Barbone, P. Latawiec, D. Yoon, A. K. Ott, M. Loncar, A. C. Ferrari and M. Atatüre, *Nat. Commun.*, 2017, **8**, 15093; (i) S. Kumar, A. Kaczmarczyk and B. D. Gerardot, *Nano Lett.*, 2015, **15**, 7567–7573; (j) J. Kern, I. Niehues, P. Tonndorf, R. Schmidt, D. Wigger, R. Schneider, T. Stiehm, S. Michaelis de Vasconcellos, D. E. Reiter, T. Kuhn and R. Bratschitsch, *Adv. Mater.*, 2016, **28**, 7101–7105; (k) G. D. Shepard, O. A. Ajayi, X. Li, X. Y. Zhu, J. Hone and S. Strauf, *2D Mater.*, 2017, **4**, 21019; (l) N. Morell, A. Reserbat-Plantey, I. Tsioutsios, K. G. Schädler, F. Dubin, F. H. L. Koppens and A. Bachtold, *Nano Lett.*, 2016, **16**, 5102–5108; (m) C. H. Liu, I. S. Kim and L. J. Lauhon, *Nano Lett.*, 2015, **15**, 6727–6731; (n) J. Lee, Z. Wang, K. He, J. Shan and P. X. L. Feng, *ACS Nano*, 2013, **7**, 6086–6091; (o) J. Chaste, A. Missaoui, S. Huang, H. Henck, Z. B. Aziza, L. Ferlazzo, A. Balan, A. T. C. Johnson, R. Braive and A. Ouerghi, *ACS Nano*, 2018, **12**, 3235–3242; (p) B. Bagchi, N. A. Hoque, N. Janowicz, S. Das and M. K. Tiwari, *Nano Energy*, 2020, **78**, 1053.
- 57 X. Hou, H. Jiang, M. K. A. Ali, H. Liu, D. Su and Z. Tian, *J. Mol. Liq.*, 2020, **311**, 113303.
- 58 Z. Bojarska, J. Kopytowski, M. Mazurkiewicz-Pawlicka, P. Bazarnik, S. Gierlotka, A. Rozen and L. Makowski, *Tribol. Int.*, 2021, **160**, 106999.
- 59 S. Kaushik, U. K. Tiwari, S. S. Pal and R. K. Sinha, *Biosens. Bioelectron.*, 2019, **126**, 501–509.
- 60 K. Peng, J. Wang, H. Wang, X. Li, P. Wan, H. Zhang and L. Bai, *Appl. Clay Sci.*, 2019, **183**, 105346.
- 61 M. Ikram, M. I. Khan, A. Raza, M. Imran, A. Ul-Hamid and S. Ali, *Phys. Rev. E*, 2020, **124**, 114246.
- 62 Ritika, M. Kaur, A. Umar, S. Mehta, S. Singh, S. Kansal, H. Fouad and O. Alothman, *Materials*, 2018, **11**(11), 2254.
- 63 M. Wang, P. Ju, J. Li, Y. Zhao, X. Han and Z. Hao, *ACS Sustainable Chem. Eng.*, 2017, **5**(9), 7878–7886.
- 64 A. J. Cheah, W. S. Chiu, P. S. Khiew, H. Nakajima, T. Saisopa, P. Songsiririthigul, S. Radiman and M. A. A. Hamid, *Catal. Sci. Technol.*, 2015, **5**(8), 4133–4143.
- 65 S. San Martin, M. J. Rivero and I. Ortiz, *Catalysts*, 2020, **10**(8), 901.
- 66 Y. Hu, X. Yu, Q. Liu, L. Wang and H. Tang, *Carbon*, 2022, **188**, 70–80.
- 67 W. Y. Lim, H. Wu, Y. F. Lim and G. W. Ho, *J. Mater. Chem. A*, 2018, **6**(24), 11416–11423.



## Review

- 68 Y. Wang, X. Tang, Z. Liu, Y. Yan, B. Yang and Z. Zhu, *New J. Chem.*, 2020, **44**, 18264–18273.
- 69 H. Tran Huu, M. D. N. Thi, V. P. Nguyen, *et al.*, *Sci. Rep.*, 2021, **11**, 14787.
- 70 M. Yusuf, S. Song, S. Park and K. H. Park, *Appl. Catal. A*, 2021, **613**, 118025.
- 71 N. Guo, Y. Zeng, H. Li, X. Xu and H. Yu, *Mater. Lett.*, 2017, **209**, 417–420.
- 72 T. Ilyas, F. Raziq, S. Ali, A. Zada, N. Ilyas, R. Shaha, Y. Wang and L. Qiao, *Mater. Des.*, 2021, **204**, 109674.
- 73 S. Kumari, R. Gusain, A. Kumar, N. Manwar, S. L. Jain and O. P. Khatri, *J. CO<sub>2</sub> Util.*, 2020, **42**, 101345.
- 74 F. Wang, D. Liu, J. Wen and X. Zheng, *J. Environ. Chem. Eng.*, 2021, **9**(5), 106042.
- 75 J. Wan, X. Du, E. Liu, Y. Hu, J. Fan and X. Hu, *J. Catal.*, 2017, **345**, 281–294.
- 76 W. Peng, Y. Chen and X. Li, *J. Hazard. Mater.*, 2016, **309**, 173–179.
- 77 (a) K. Jaiswal, Y. R. Girish, P. Behera and M. De, *ACS Org. Inorg. Au*, 2022, **2**, 205–213; (b) Y. R. Girish, R. Biswas and M. De, *Chem.–Eur. J.*, 2018, **24**(52), 13871–13878; (c) Y. R. Girish, R. Biswas and M. De, *Catal. Sci. Technol.*, 2019, **9**, 1201–1207.
- 78 H. H. Shin, E. Kang, H. Park, T. Han, C. H. Lee and D. K. Lim, *J. Mater. Chem. A*, 2017, **5**, 24965–24971.
- 79 P. Xing, P. Chen, Z. Chen, X. Hu, H. Lin, Y. Wu, L. Zhao and Y. He, *ACS Sustainable Chem. Eng.*, 2018, **6**(11), 14866–14879.
- 80 H. Li, Y. Liu, Y. Liu, L. Wang, R. Tang, P. Deng, Z. Xu, B. Haynes, C. Sun and J. Huang, *Appl. Catal. B*, 2021, **281**, 119476.
- 81 X. Liu, X. Han, Z. Liang, Y. Xue, Y. Zhou, X. Zhang, H. Cui and J. Tian, *J. Colloid Interface Sci.*, 2022, **605**, 320–329.
- 82 M. S. Yu, S. C. Jesudass, S. Surendran, J. Y. Kim, U. Sim and M. K. Han, *Appl. Mater. Interfaces*, 2022, **14**(28), 31889.
- 83 H. Cao, C. Jia, H. Zhang, G. Hou, Y. Tang and G. Zheng, *New J. Chem.*, 2021, **45**, 10608.
- 84 N. Kumar, S. Kumar, R. Gusain, N. Manyala, S. Eslava and S. S. Ray, *ACS Appl. Energy Mater.*, 2020, **3**(10), 9897–9909.

